

## DESCRIPTION

VERTICAL CAVITY SURFACE EMITTING SEMICONDUCTOR LASER,  
LIGHT EMISSION DEVICE, AND OPTICAL TRANSMISSION SYSTEM

5

TECHNICAL FIELD

The present invention relates to a semiconductor laser, and particularly, a vertical cavity surface emitting laser device, and a light emission 10 device and an optical transmission system.

BACKGROUND ART

In these years, the optical transmission technique is widely used not only in major transmission 15 networks but also in LANs (Local Area Networks), home networks, or access systems. For example, in Ethernet, a transmission rate of 10 Gbps has been obtained, a higher transmission rate will be required in the near future, and an optical transmission system is expected to provide 20 a transmission capacity higher than 10 Gbps.

In a light source used in optical transmission having a transmission rate lower than 10 Gbps, a direct modulation scheme is primarily employed in which the power of output light is modulated by modulating an 25 injection current flowing in a semiconductor laser.

However, it is difficult to operate a semiconductor laser at a modulation frequency higher than 10 GHz with the direct modulation scheme.

To solve this problem, a modulation scheme has 5 been developed in which light output from a semiconductor laser is modulated by an external modulator. However, in this external modulation scheme, size of modules is large, and a large number of parts are used; hence, cost is high. For this reason, even though an optical transmission 10 technique using an external modulator is applied in expensive systems such as major transmission networks, it is not suitable for personal systems, such as LANs or home networks.

On the other hand, it has been studied to use 15 a vertical cavity surface emitting laser (VCSEL) as a light source used in LANs or for optical interconnections. The VCSEL has low power consumption compared to traditional edge-emitting lasers, and because cleavage is not needed during the fabrication process, it is possible 20 to inspect the device in wafer form, hence the fabrication cost can be reduced. For this reason, it is expected to use a vertical cavity surface emitting laser (VCSEL) by means of direct modulation as a light source in LANs or for optical interconnections involving a 25 transmission capacity higher than 10 Gbps.

The following methods have been proposed to perform fast speed modulation for the VCSEL.

Japanese Laid-Open Patent Application No. 2002-185079 (referred to as "reference 1" hereinafter) 5 discloses a technique in which a current is injected into an active region without passing through an upper multilayer reflecting mirror, and a modulation doped stacked structure able to generate two-dimensional carriers is provided so as to reduce a lateral resistance, 10 and this reduces the resistance of the VCSEL and spreads an electrical modulation region, which is restricted by a resistance R and a capacitance C.

Japanese Laid-Open Patent Application No. 2002-204039 (referred to as "reference 2" hereinafter) 15 discloses a technique in which a quantum well layer capable of intersubband absorption is arranged near a light emission layer; when modulated optical signals are input, due to the intersubband absorption of the quantum well layer, a carrier distribution, a carrier density of 20 the light emission layer, and light emission output are modulated; as a result, high speed is obtainable with the response speed not being influenced by a CR time constant or a carrier transportation effect.

Japanese Laid-Open Patent Application No. 7-  
25 249824 (referred to as "reference 3" hereinafter)

discloses a technique in which horizontal cavity  
semiconductor lasers for optically exciting a VCSEL are  
stacked on the same substrate, a forbidden band width of  
an active layer of the VCSEL is set to be less than a  
5 forbidden band width of the horizontal cavity  
semiconductor lasers to increase optical excitation  
efficiency, and modulation optical signals from the  
horizontal cavity semiconductor lasers are input for  
external modulation; thereby, the modulation frequency of  
10 the VCSEL is increased.

In IEICE technical report, Optoelectronics  
2003-218, LQE3003-155 (referred to as "reference 4"  
hereinafter), a technique is disclosed in which a DFB  
laser beam is injected into a VCSEL and is synchronized  
15 with an oscillation wavelength of the VCSEL (this is the  
so-called "injection lock"); due to this, a relaxation  
oscillation frequency of the VCSEL is increased to be  
22.8 GHz.

As described above, in reference 1, response  
20 speed is improved when electrical modulation signals  
output from a driver circuit modulate the carrier density  
of the light emission layer of the VCSEL. In references 2  
and 3, the optical modulation signals are input from  
outside to reduce influence of a delay of an electrical  
25 response speed when a current flows into the device.

However, none of the techniques in references 1, 2 and 3 can increase the relaxation oscillation frequency, which represents a frequency at which the speed of induced emission can no longer follow the change 5 of the carrier density in the light emission layer. Due to this, the modulation speed is limited by the relaxation oscillation frequency.

In reference 4, a laser beam is injected from outside and is synchronized with the oscillation mode of 10 the VCSEL; thereby, the photon density inside the VCSEL is increased. Since the internal photon density is associated with the relaxation oscillation frequency, by increasing the internal photon density, the relaxation oscillation frequency of the VCSEL can be increased. 15 However, in the technique shown in reference 4, it is necessary to accurately set the wavelength of the laser beam injected from outside to be exactly equal to the wavelength of the oscillation mode of the VCSEL. Even when the wavelength deviates by only a few nanometers to 20 be out of synchronization, it is impossible to increase the relaxation oscillation frequency of the VCSEL. For this reason, devices for tuning the wavelength and for temperature control are required, thus the overall device become complicated.

DISCLOSURE OF THE INVENTION

It is a general object of the present invention to solve one or more of the problems of the related art.

5 A specific object of the present invention is to provide a semiconductor laser that can be used to form a VCSEL (vertical cavity surface emitting laser) light emission device with a simplified configuration, the VCSEL light emission device being used in optical  
10 transmission at a transmission rate higher than 10 Gbps per channel, and a light emission device, and an optical transmission system.

According to a first aspect of the present invention, there is provided a vertical cavity surface emitting semiconductor laser, comprising: a resonator that is arranged on a substrate and includes a first active region able to emit light in response to injection of an electrical current therein and a second active region able to emit light in response to external excitation light; and plural multilayer film reflecting mirrors that sandwich the resonator from two opposite sides, respectively, wherein both the first active region and the second active region have gains at a wavelength the same as a resonance mode of the resonator.

25 According to the present invention, in

addition to a first active region able to emit light in response to injection of an electrical current, a second active region is provided in the resonator which is able to emit light in response to external excitation light.

5 As a result, the photon density generated due to the external excitation light is added to the photon density generated due to injection of an electrical current at the same mode, and the total photon density in the vertical cavity surface emitting semiconductor laser is

10 increased. Due to this, it is possible to increase a relaxation oscillation frequency of the vertical cavity surface emitting semiconductor laser, and attain high speed modulation.

According to a second aspect of the present

15 invention, there is provided a vertical cavity surface emitting semiconductor laser, comprising: a plurality of resonators that are arranged on a substrate and optically coupled with each other to form a resonance mode, one of the resonators having a first active region able to emit

20 light in response to injection of an electrical current, each of the other resonators having a second active region able to emit light in response to external excitation light; and plural multilayer film reflecting mirrors that sandwich the resonators from two opposite

25 sides, respectively, wherein the first active region and

the second active regions have gains at a wavelength the same as the resonance mode.

According to the present invention, the vertical cavity surface emitting semiconductor laser includes plural resonators optically coupled with each other, one of the resonators has a first active region able to emit light in response to injection of an electrical current, and each of the other resonators has a second active region able to emit light in response to external excitation light. As a result, the photon density generated due to the external excitation light is added to the photon density generated due to injection of an electrical current at the same mode, and the total photon density in the vertical cavity surface emitting semiconductor laser is increased. Therefore, it is possible to increase the relaxation oscillation frequency of the vertical cavity surface emitting semiconductor laser and attain high speed modulation.

In addition, because the first active region and the second active region are separated from each other, it is possible to prevent optical crosstalk from the external excitation light.

As an embodiment, plural second active regions are provided.

According to the present invention, because

plural second active regions are provided, gain saturation can hardly occur even at a high photon density, therefore, it is possible to further increase the relaxation oscillation frequency of the vertical cavity surface emitting semiconductor laser.

As an embodiment, each of the first active region and the second active regions includes a mixed crystalline semiconductor of nitrogen and group-V elements.

According to the present invention, because each of the first active region and the second active regions includes a mixed crystalline semiconductor of nitrogen and group-V elements, it is possible to form a vertical cavity surface emitting semiconductor laser operating at a wavelength of  $1.31 \mu\text{m}$ , at which dispersion of a silica optical fiber is zero, and form a light emission device suitable for high data rate transmission.

As an embodiment, the first active region includes a multiple quantum well structure obtained by stacking plural quantum well layers and barrier layers, and each of the barrier layers is doped with p-type impurities at a concentration in a range from  $1 \times 10^{18} \text{ cm}^{-3}$  to  $1 \times 10^{19} \text{ cm}^{-3}$ .

According to the present invention, because

the first active region includes a multiple quantum well structure obtained by stacking plural quantum well layers and barrier layers, and each of the barrier layers is doped with p-type impurities at a concentration in a  
5 range from  $1 \times 10^{18} \text{ cm}^{-3}$  to  $1 \times 10^{19} \text{ cm}^{-3}$ , it is possible to increase the relaxation oscillation frequency of the vertical cavity surface emitting semiconductor laser.

According to a third aspect of the present invention, there is provided a light emission device,  
10 comprising: an external excitation light source, and a vertical cavity surface emitting semiconductor laser that includes a resonator that is arranged on a substrate and includes a first active region able to emit light in response to injection of an electrical current therein  
15 and a second active region able to emit light in response to external excitation light, the first active region and the second active region having gains at a wavelength the same as a resonance mode of the resonator, and plural multilayer film reflecting mirrors that sandwich the resonator from two opposite sides, respectively, wherein  
20 a wavelength of the external excitation light source is less than or equal to a wavelength corresponding to a bandgap of the second active region.

According to the present invention, it is  
25 possible to realize high data rate optical transmission

over 10 Gbps.

As an embodiment, the external excitation light source is a semiconductor laser.

According to the present invention, because  
5 the external excitation light source is a semiconductor laser, it is possible to make the light emission device compact and reduce power consumption.

As an embodiment, the external excitation light source is a vertical cavity surface emitting  
10 semiconductor laser.

According to the present invention, because the external excitation light source is a vertical cavity surface emitting semiconductor laser, it is possible to further reduce power consumption of the light emission  
15 device and reduce cost of the light emission device.

As an embodiment, the external excitation light source and the vertical cavity surface emitting semiconductor laser are integrated together.

According to the present invention, because  
20 the external excitation light source and the vertical cavity surface emitting semiconductor laser are integrated together, it is possible to make the light emission device compact, reduce the number of parts in the light emission device, and reduce cost of the light  
25 emission device.

According to a fourth aspect of the present invention, there is provided a light emission device comprising: an external excitation light source; and a vertical cavity surface emitting semiconductor laser that

5 includes a plurality of resonators that are arranged on a substrate and optically coupled with each other to form a resonance mode, one of the resonators having a first active region able to emit light in response to injection of an electrical current, each of the other resonators

10 having a second active region able to emit light in response to external excitation light; and a plurality of multilayer film reflecting mirrors which mirrors sandwich the resonators from two opposite sides, respectively; wherein the first active region and the second active

15 regions have gains at a wavelength the same as the resonance mode.

According to a fifth aspect of the present invention, there is provided an optical transmission system, comprising: a light emission device, which

20 includes an external excitation light source, and a vertical cavity surface emitting semiconductor laser wherein the vertical cavity surface emitting semiconductor laser includes a resonator that is arranged on a substrate and includes a first active region able to

25 emit light in response to injection of an electrical

current therein and a second active region able to emit light in response to external excitation light, the first active region and the second active region having gains at a wavelength the same as the resonance mode of the 5 resonator, and plural multilayer film reflecting mirrors that sandwich the resonator from two opposite sides, respectively, wherein a wavelength of the external excitation light source is less than or equal to a wavelength corresponding to a bandgap of the second 10 active region.

According to a sixth aspect of the present invention, there is provided an optical transmission system, comprising a light emission device, which includes an external excitation light source; and a 15 vertical cavity surface emitting semiconductor laser, which includes a plurality of resonators that are arranged on a substrate and optically coupled with each other to form a resonance mode, one of the resonators having a first active region able to emit light in 20 response to injection of an electrical current, each of the other resonators having a second active region able to emit light in response to external excitation light; and a plurality of multilayer film reflecting mirrors which mirrors sandwich the resonators from two opposite 25 sides, respectively; wherein the first active region and

the second active regions have gains at a wavelength the same as the resonance mode.

According to the present invention, it is possible to construct an optical transmission system for 5 high data rate optical transmission over 10 Gbps at low cost.

These and other objects, features, and advantages of the present invention will become more apparent from the following detailed description of 10 preferred embodiments given with reference to the accompanying drawings

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic cross-sectional view 15 illustrating an example of the vertical cavity surface emitting semiconductor laser (VCSEL) according to the present invention;

FIG. 2 is a schematic cross-sectional view illustrating an example of a light emission device, which 20 includes the vertical cavity surface emitting semiconductor laser as shown in FIG. 1;

FIG. 3 is a schematic cross-sectional view illustrating another example of the vertical cavity surface emitting semiconductor laser (VCSEL) according to 25 the present invention;

FIG. 4 is a schematic cross-sectional view illustrating an example of a light emission device including the vertical cavity surface emitting semiconductor laser as shown in FIG. 3;

5 FIG. 5A is a schematic cross-sectional view illustrating another example of the vertical cavity surface emitting semiconductor laser (VCSEL) according to the present invention;

10 FIG. 5B is a schematic cross-sectional view illustrating the semiconductor laser 521 along the A-B line in FIG. 5A;

15 FIG. 6 is a schematic cross-sectional view illustrating another example of the vertical cavity surface emitting semiconductor laser (VCSEL) according to the present invention;

FIG. 7 is a schematic view illustrating an optical transmission system according to the present invention; and

20 FIG. 8 is a schematic cross-sectional view illustrating an example of the vertical cavity surface emitting semiconductor laser (VCSEL) according to the present invention.

BEST MODE FOR CARRYING OUT THE INVENTION

25 Below, preferred embodiments of the present

invention are explained with reference to the accompanying drawings.

First Embodiment

5           The present embodiment relates to a vertical cavity surface emitting semiconductor laser, which includes a resonator arranged on a substrate, and multilayer film reflecting mirrors sandwiching the resonator from two opposite sides, respectively. The  
10          resonator includes a first active region that is able to emit light in response to injection of an electrical current, and a second active region that is able to emit light in response to external excitation light. Both the first active region and the second active region have  
15          gains at a wavelength the same as a resonance mode of the resonator.

          In direct modulation of a semiconductor laser, a few factors may impose limitations on the modulation bands, for example, a CR time constant, a carrier  
20          transportation effect, or a relaxation oscillation frequency. Especially, the relaxation oscillation frequency indicates a limiting frequency at which the speed of induced emission can no longer follow the change of carrier density in the light emission layer, and it  
25          imposes an intrinsic limitation on the direct modulation.

Generally, the relaxation oscillation frequency  $f_r$  can be expressed by the following formula (1).

5                   
$$f_r = \frac{1}{2\pi} \sqrt{\frac{\Gamma g S}{\tau_p}} \quad (1)$$

where,  $\Gamma$  represents an optical confinement coefficient,  $g$  represents differential gain,  $S$  represents photon density, and  $\tau_p$  represents photon lifetime.

10                  According to the formula (1), the relaxation oscillation frequency  $f_r$  increases along with the photon density  $S$ . However, if carriers are highly injected into the light emission layer, gain saturation occurs because of carrier overflow or heating of the laser device, and 15 the photon density cannot be increased any more. For this reason, the relaxation oscillation frequency  $f_r$  is limited to about 10 GHz.

In the vertical cavity surface emitting semiconductor laser of the present embodiment, in 20 addition to the first active region being able to emit light in response to injection of an electrical current, the resonator also includes the second active region which is able to emit light in response to external excitation light, but without a current injection

mechanism. As a result, by modulating an injection current flowing in the first active region, the carrier density in the first active region changes, and the intensity of output light is modulated. Further, in the  
5 second active region, light emission is induced by continuous injection of the external excitation light, and when the intensity of the excitation light is increased to be over a specified threshold value, laser oscillation occurs.

10 The first active region, which emits light in response to injection of an electrical current, and the second active region, which emits light in response to external excitation light, are provided in the same resonator, and both the first active region and the  
15 second active region have gains at a wavelength the same as the resonance mode of the resonator. Therefore, light emission due to oscillation in the first active region caused by current injection and light emission due to oscillation in the second active region caused by  
20 external excitation light are at the same oscillation frequency, that is, their oscillation modes are synchronized with each other.

Hence, the photon density generated by the external excitation light is added at the same mode to  
25 the photon density generated by current injection, while

in the related art only the photon density generated by current injection is present. Therefore, the photon density  $S$  in the laser device can be increased, and it is possible to increase the relaxation oscillation frequency  
5  $f_r$  of the vertical cavity surface emitting semiconductor laser (VCSEL), and attain high speed modulation.

For example, the external excitation light can be injected in a lateral direction of the VCSEL, or in a direction perpendicular to the substrate.

10 In the VCSEL disclosed in the above mentioned reference 4, a laser beam synchronized with an oscillation mode of the VCSEL is injected into the VCSEL from outside, thereby increasing the photon density inside the VCSEL. For this purpose, it is necessary to  
15 accurately set the wavelength of the laser beam injected from the outside to be exactly equal to the wavelength of the oscillation mode of the VCSEL.

In contrast, in the present embodiment, because the external excitation light, that is, the laser  
20 beam injected from the outside, is used to optically excite the second active region, the external excitation light can have any wavelength provided that the external excitation light can be absorbed by the second active region. Hence, it is not necessary to accurately control  
25 the wavelength of the excitation light, and this makes

the structure of the laser device simple.

The technique disclosed in the aforementioned reference 3 is similar to the present embodiment in the aspect that a light beam is injected to excite the VCSEL,  
5 but it is different from the present embodiment in the aspect that an active layer into which a current is injected and an active layer into which the light beam is injected are in the same layer.

When the current injection active layer and  
10 the light injection active layer are in the same layer, because the carriers generated due to light excitation are added to the carrier density generated due to current injection, it is difficult to improve the gain saturation caused by carrier overflow in the active layer.

15 In contrast, in the present embodiment, because the first active region, which emits light in response to current injection, and the second active region, which emits light in response to external excitation light, are separated from each other, it is  
20 possible to prevent carrier storage in the first active region, into which a current is injected, and to increase the photon density inside the VCSEL. As a result, it is possible to increase the relaxation oscillation frequency compared to the related art.

25 In addition, in Electronics Letters, 2002, Vol.

28, pp. 278-280 (referred to as "reference 5", hereinafter), a VCSEL structure is disclosed which includes two active regions in the resonator. The VCSEL structure in reference 5 has three terminals, and 5 electrical currents are injected into the two active regions independently. However, if current injection active regions are close to each other, a junction voltage is applied on the pn junction of each of the active regions, and heat generated in the VCSEL is large.

10 In contrast, in the present embodiment, one of the two active regions is optically excited for light emission, but does not have a current injection mechanism; hence, heat generation in the VCSEL can be reduced.

15 Because a pn junction is not formed in the second active region, which is excited by external excitation light and emits light, the second active region can be formed in any of a n-type semiconductor layer, a p-type semiconductor layer, or a non-doped 20 semiconductor layer, thereby, increasing the degree of freedom when designing the VCSEL structure.

It is desirable that the first active region and the second active region be at anti-node positions of an optical standing wave distribution in the VCSEL device. 25 Due to this, coupling efficiency between the optical

standing wave and the active region can be improved, and a threshold can be lowered.

In order to improve temperature characteristics of the VCSEL device, the wavelength at 5 the peak of the gain of the active region at room temperature can be shifted to the short wavelength side relative to the oscillation mode wavelength. When shifting the wavelength, it is not required to set the wavelength shift of the first active region to be equal 10 to the wavelength shift of the second active region. It is sufficient if the oscillation mode wavelength is within the gain spectrum band of each of the active regions.

15 Second Embodiment

The present embodiment relates to a vertical cavity surface emitting semiconductor laser, which includes plural resonators arranged on a substrate and optically coupled with each other to form a resonance 20 mode, and plural multilayer film reflecting mirrors sandwiching the resonators from two opposite sides, respectively. One of the resonators has a first active region able to emit light in response to injection of an electrical current, and each of other resonators has a 25 second active region able to emit light in response to

external excitation light. The first active region and the second active regions have gains at a wavelength of the same resonance mode.

According to the present embodiment, the  
5 vertical cavity surface emitting semiconductor laser includes plural resonators optically coupled with each other, one of the resonators has a first active region able to emit light in response to injection of an electrical current, and each of the other resonators has  
10 a second active region able to emit light in response to external excitation light.

As a result, by modulating an injection current flowing in the first active region, the carrier density in the first active region changes, and the  
15 intensity of output light is modulated. Further, in the second active region, induced emission is caused by continuous injection of the external excitation light, and when the intensity of the excitation light is increased to be over a specified threshold value, laser  
20 oscillation occurs.

In the present embodiment, the first active region, which emits light in response to injection of an electrical current, and the second active region, which emits light in response to external excitation light, are  
25 provided in different resonators, but these resonators

optically couple with each other and form a resonance mode. In addition, the first active region and the second active regions have gains at a wavelength the same as the resonance mode. Therefore, light emission due to  
5 oscillation in the first active region caused by current injection and light emission due to oscillation in the second active region caused by external excitation light are at the same oscillation frequency, that is, their oscillation modes are synchronized with each other.

Hence, the photon density generated by the external excitation light is added at the same mode to the photon density generated due to current injection. In contrast, in the related art, only the photon density generated by current injection is present. Therefore, the  
15 photon density in the VCSEL device is increased, and it is possible to increase the relaxation oscillation frequency  $f_r$  of the VCSEL device, and attain high speed modulation.

Because the first active region, which is excited by current injection and emits light, and the second active region, which is excited by external excitation light and emits light, are provided in different resonators, the first active region and the second active region are separated from each other.  
20

It is known that when the first active region

and the second active region are arranged to be close to each other, a portion of the excitation light injected from the outside is also injected into the first active region, and results in an increase of the carrier density  
5 in the first active region.

In contrast, in the present embodiment, because the first active region and the second active region are separated from each other, the excitation light injected from the outside is only injected into the  
10 second active region, therefore, it is possible to prevent leakage of the excitation light into the first active region and prevent optical crosstalk from the external excitation light.

15                   Third Embodiment

The present embodiment relates to a vertical cavity surface emitting semiconductor laser, which includes plural second active regions that are excited by external excitation light and emit light, in addition to  
20 the structure as described in one of the first embodiment and the second embodiment.

According to the present embodiment, because of an increased number of active regions able to generate gains, it is possible to reduce density of the carriers  
25 stored in the active regions so that gain saturation can

hardly occur even at a high photon density. Therefore, it is possible to further increase the relaxation oscillation frequency of the vertical cavity surface emitting semiconductor laser.

5           The plural active regions are excited by external excitation light, but do not have current injection mechanisms. It is known that if there are plural current injection active regions, it is necessary to increase the number of electrode terminals, and this  
10          makes the structure of the device complicated. Due to this complication, the number of steps in the fabrication process increases, and the yield decreases.

It is desirable that the second active regions be located at anti-node positions of an optical standing  
15          wave distribution in the VCSEL device. Due to this, it is possible to easily increase the number of the second active regions, and to reduce cost.

Usually, the second active regions, which are excited by external excitation light, emit light, and do  
20          not have current injection mechanisms, are provided in a resonator sandwiched by distributed Bragg reflection mirrors (DBR). However, the second active regions may be provided in the DBR. This is because light may leak out of the resonator to the DBR side, and this light can be  
25          strengthened in the second active regions provided in the

DBR. However, the light intensity at anti-node positions of the optical standing wave distribution in the VCSEL device is attenuated when the distance to the resonator is far; hence, the coupling efficiency between light in 5 the VCSEL device and the active layers decreases. For this reason, when the second active regions, which are excited by external excitation light, emit light, and do not have current injection mechanisms, are provided in the DBR, it is desirable that the second active regions 10 be arranged within a distance to the resonator less than three periods.

Fourth Embodiment

The present embodiment relates to a vertical 15 cavity surface emitting semiconductor laser, wherein each active region includes a mixed crystalline semiconductor of nitrogen and group-V elements, in addition to the structure as described in one of the first embodiment through the third embodiment.

20 The mixed crystalline semiconductor materials of nitrogen and group-V elements may include GaNAs, GaInNAs, GaNAsP, GaInNAsP, GaNAsSb, GaInNAsSb, GaNAsPSb, GaInNAsPSb. These mixed crystalline semiconductor materials belong to long-wavelength material groups which 25 are capable of crystal growth on a GaAs susbtrate. Below,

GaInNAs is taken as an example for descriptions.

Because GaInNAs can have a conduction band electron confinement barrier height as high as 300 meV or even higher relative to a barrier height of GaAs, GaInNAs 5 is able to prevent electron overflow and has good temperature characteristics.

In addition, because a distributed Bragg reflection mirror is usable, which is formed from AlGaAs-based materials, and has high reflectivity and high 10 thermal conductivity, a vertical cavity surface emitting semiconductor laser can be constructed which has high performance in the long-wavelength band.

As described above, the object of the present invention is to provide a direct modulation VCSEL able to 15 improve the modulation frequency and thereby enabling high data rate optical transmission over 10 Gbps. At transmission rates higher than 10 Gbps, because of dispersion in a silica optical fiber, the transmission distance is limited. By forming the first active region 20 and the second active region with mixed crystalline semiconductors of nitrogen and group-V elements, such as GaInNAs, it is possible to form a vertical cavity surface emitting semiconductor laser operating at a wavelength of 1.31  $\mu$ m, at which dispersion in a silica optical fiber 25 is zero, and this allows one to take full advantage of

high speed modulation of the present invention.

Fifth Embodiment

The present embodiment relates to a vertical  
5 cavity surface emitting semiconductor laser, wherein the  
first active region that is excited by current injection  
for light emission includes a multiple quantum well (MQW)  
structure formed by stacking plural quantum well layers  
and barrier layers, and each of the barrier layers is  
10 doped with p-type impurities at a concentration in a  
range from  $1 \times 10^{18} \text{ cm}^{-3}$  to  $1 \times 10^{19} \text{ cm}^{-3}$ , in addition to  
the structure as described in one of the first embodiment  
through the fourth embodiment.

In the present embodiment, because the barrier  
15 layers in the multiple quantum well (MQW) structure are  
doped with p-type impurities at a concentration in a  
range from  $1 \times 10^{18} \text{ cm}^{-3}$  to  $1 \times 10^{19} \text{ cm}^{-3}$ , it is possible  
to reduce the density of electrons required to be  
injected for laser oscillation, and to increase the  
20 differential gain g. According to the afore mentioned  
formula (1), by combining the effect of increasing the  
differential gain g and the effect of increasing the  
photon density S in the VCSEL device, it is possible to  
further increase the relaxation oscillation frequency of  
25 the VCSEL device.

When the concentration of the p-type impurities is less than  $1 \times 10^{18} \text{ cm}^{-3}$ , little increase of the differential gain  $g$  can be obtained. Meanwhile, when the concentration of the p-type impurities is greater than  $1 \times 10^{19} \text{ cm}^{-3}$ , crystallinity of the barrier layers degrades. Therefore, it is desirable that the p-type impurities be doped at a concentration in a range from  $1 \times 10^{18} \text{ cm}^{-3}$  to  $1 \times 10^{19} \text{ cm}^{-3}$ .

The p-type impurities may include C, Zn, Be, Mg; C is preferable because thermal diffusion of C is small even at high doping concentration, hence a sharp doping profile is obtainable.

Sixth Embodiment

The present embodiment relates to a light emission device, which includes a vertical cavity surface emitting semiconductor laser as described in one of the first embodiment through the fifth embodiment, and an external excitation light source, wherein the wavelength of the external excitation light source is less than or equal to a wavelength corresponding to a bandgap of a second active region that is excited by external excitation light for light emission.

According to the present embodiment, the light emission device includes a vertical cavity surface

emitting semiconductor laser as described in one of the first embodiment through the fifth embodiment, and an external excitation light source, where the external excitation light source emits light having a wavelength  
5 less than or equal to a wavelength corresponding to the bandgap of the second active region. Due to this configuration, the second active region, which does not have a current injection mechanism, is excited by external excitation light for light emission. By using  
10 the modulation signal as the electrical signal that ought to be applied to the first active region, which is excited by current injection for light emission, the light output of the VCSEL is modulated.

The relaxation oscillation frequency of the  
15 VCSEL increases along with increase of the photon density in the VCSEL of light generated by oscillation induced by the external excitation light. With a VCSEL having a higher relaxation oscillation frequency, the light emission device of the present embodiment is capable of  
20 high speed modulation, and this enables high data rate optical transmission over 10 Gbps.

Seventh Embodiment

The present embodiment relates to a light  
25 emission device the same as the light emission device in

the sixth embodiment, and furthermore, the external excitation light source is a semiconductor laser in the present embodiment.

According to the present embodiment, because  
5 the external excitation light source is a semiconductor laser, it is possible to make the light emission device compact and reduce power consumption.

The semiconductor laser used as the external excitation light source can be a Fabry-Perot resonating  
10 semiconductor laser, a distributed feedback (DFB) laser, or a distributed Bragg reflection semiconductor laser.

#### Eighth Embodiment

The present embodiment relates to a light  
15 emission device the same as the light emission device in the sixth embodiment; furthermore, the external excitation light source is a vertical cavity vertical cavity surface emitting semiconductor laser (VCSEL).

The VCSEL has low power consumption compared  
20 to an edge-emitting laser, and can be fabricated at low cost. Therefore, with the external excitation light source being the VCSEL, it is possible to further reduce power consumption and fabrication cost of the light emission device.

Ninth Embodiment

The present embodiment relates to a light emission device the same as the light emission device in the seventh embodiment or the eighth embodiment; 5 furthermore, the vertical cavity surface emitting semiconductor laser as described in one of the first embodiment through the fifth embodiment and the external excitation light source are integrated together.

According to the present embodiment, because 10 the external excitation light source and the vertical cavity surface emitting semiconductor laser are integrated together, it is possible to further reduce size of the light emission device, reduce the number of parts in the light emission device, and lower the cost of 15 the light emission device.

In addition, when an edge emitting semiconductor laser is used as the external excitation light source, the VCSEL and edge emitting semiconductor laser can be arranged side by side to form a structure 20 enabling optical excitation in the lateral direction. Further, when a vertical cavity surface emitting semiconductor laser (VCSEL) is used as the external excitation light source, the VCSEL for outputting modulation light and the VCSEL for optical excitation can 25 be stacked in a direction perpendicular to the substrate.

Meanwhile, Electronics Letters, 1998, Vol. 34,  
pp. 1405-1407 (referred to as "reference 6", hereinafter)  
discloses a stacked structure formed by stacking a VCSEL  
at a wavelength of  $0.85 \mu\text{m}$  for used of optical  
5 excitation and a VCSEL at a wavelength of  $1.3 \mu\text{m}$ . In  
reference 6, however, the VCSEL at the  $1.3 \mu\text{m}$  band does  
not have a current injection mechanism, and modulation of  
the light at  $1.3 \mu\text{m}$  is carried out by the VCSEL at  $0.85$   
 $\mu\text{m}$  by means of direct modulation. For this reason, the  
10 modulation frequency is limited to the relaxation  
oscillation frequency of the VCSEL at  $0.85 \mu\text{m}$ . Therefore,  
different from the present invention, this structure in  
reference 6 cannot increase the relaxation oscillation  
frequency of the VCSEL itself. Namely, the technique in  
15 reference 6 is different from the present embodiment in  
both structure and operating principle.

#### 10th Embodiment

The present embodiment relates to an optical  
20 transmission system, which includes a light emission  
device as described in one of the sixth embodiment  
through the ninth embodiment.

According to the present embodiment, it is  
possible to perform high speed modulation over 10 GHz by  
25 direct modulation of a VCSEL. Due to this, it is possible

to construct an optical transmission system for high data rate optical transmission over 10 Gbps at low cost without external modulators or electron cooling devices.

5           Example 1

FIG. 1 is a schematic cross-sectional view illustrating an example of the vertical cavity surface emitting semiconductor laser (VCSEL) according to the present invention.

10           As illustrated in FIG. 1, a non-doped distributed Bragg reflection mirror (DBR) 102 is disposed on a semi-insulating GaAs substrate 101.

The non-doped distributed Bragg reflection mirror (DBR) 102 is formed by alternately stacking a non-doped  $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$  layer and a non-doped  $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$  layer, each of which has a thickness of 1/4 wavelength.

In addition, a first spacer layer 103 formed from  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ , a multiple quantum well active region 104 formed from  $\text{GaAs}/\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ , acting as the second active region, a second spacer layer 105 formed from n-type  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ , a multiple quantum well active region 106 formed from  $\text{GaAs}/\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ , acting as the first active region, a third spacer layer 107 formed from  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ , a p-type AlAs layer 108, and a p-type DBR 109 are stacked sequentially on the non-doped distributed

Bragg reflection mirror (DBR) 102.

Here, the p-type DBR 109 is formed by alternately stacking a p-type  $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$  layer and a p-type  $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$  layer, each of which has a thickness of 5  $1/4$  wavelength.

The stacked structure is etched from the top surface thereof up to the middle of the second spacer layer 105 to make the etched portion of the stacked structure a cylindrical shape, thereby forming a first 10 mesa structure. In addition, the stacked structure is further etched up to the non-doped distributed Bragg reflection mirror (DBR) 102 to make the etched portion of the stacked structure a cylindrical shape, thereby forming a second mesa structure larger than the first 15 mesa structure.

The p-type AlAs layer 108 is selectively oxidized from a side surface of the first mesa structure, thereby, forming an  $\text{AlO}_x$  insulating region 110.

A p-side ring electrode 112 is formed on the 20 p-type DBR 109 except a light outgoing portion, and an n-side electrode 113 is formed on the bottom of the first mesa structure (the top of the second mesa structure). A light-shielding layer 111 is arranged on the side surface of the first mesa structure. For example, the light-shielding layer 111 may be metal with an insulating layer. 25

In the VCSEL illustrated in FIG. 1, holes injected from the p-side ring electrode 112 and electrons injected from the n-side electrode 113 recombine and result in light emission in the multiple quantum well 5 first active region 106 formed from GaAs/Al<sub>0.3</sub>Ga<sub>0.7</sub>As, which emitted light is at a wavelength of 0.85 μm. At this moment, since the current is blocked by the AlO<sub>x</sub> insulating region 110, the current is concentrated beneath the portion of the p-type AlAs layer 108 not 10 being selectively oxidized; hence the current distribution is narrowed.

The light emitted from the first active region 106 resonates in the resonator between the non-doped distributed Bragg reflection mirror (DBR) 102 and the p-type DBR 109, and a laser beam is emitted upward perpendicular to the substrate.

According to the present embodiment, the VCSEL includes the multiple quantum well second active region 104 formed from GaAs/Al<sub>0.3</sub>Ga<sub>0.7</sub>As, in addition to the 15 multiple quantum well first active region 106 formed from GaAs/Al<sub>0.3</sub>Ga<sub>0.7</sub>As, which emits light due to current injection.

The multiple quantum well second active region 104 does not have an electrode for injecting a current. 25 Instead, a window for injecting external excitation light

from the side surface of the second active region 104 is provided on the side surface of the second mesa structure. In addition, the light-shielding layer 111 arranged on the side surface of the first mesa structure has the 5 function of preventing the first active region 106 from being irradiated by the external excitation light.

With the excitation light being continuously injected from the outside to the second active region 104, light is emitted from the second active region 104 having 10 a wavelength corresponding to a bandgap of the second active region 104 at  $0.85 \mu\text{m}$ . When the intensity of the excitation light is increased to be over a specified threshold value, externally-excited laser oscillation occurs in the VCSEL.

Because the first active region 106 has the same bandgap as the second active region 104, and the laser oscillation occurs in the same resonator formed between the non-doped distributed Bragg reflection mirror (DBR) 102 and the p-type DBR 109, the light generated by 20 oscillation induced by current injection into the first active region 106 and the light generated by oscillation induced by optically exciting the second active region 104 have the same wavelength.

With the excitation light being continuously 25 injected into the second active region 104 to induce

oscillation in the second active region 104, by  
modulating the injection current flowing in the first  
active region 106, the carrier density in the first  
active region 106 changes, and the intensity of the  
output laser is modulated. Therefore, the photon density  
in the second active region 104 generated by the external  
excitation light is added at the same mode to the photon  
density generated in the first active region 106 by  
current injection. Hence, the photon density in the VCSEL  
can be increased, and it is possible to increase the  
relaxation oscillation frequency  $f_r$  of the VCSEL, and  
attain high speed modulation.

Because the first active region 106, which is  
excited by current injection, and the second active  
region 104, which is excited by external excitation light,  
are separated from each other, the photon density in the  
VCSEL can be increased with a relatively low carrier  
density in the first active region 106. Hence, it is  
possible to prevent gain saturation induced by carrier  
overflow in the first active region 106 into which a  
current is injected. Therefore, it is possible to  
increase the relaxation oscillation frequency  $f_r$  of the  
VCSEL, and attain high speed modulation.

The external excitation light injected into  
the second active region 104 can have any wavelength

provided that the external excitation light can be absorbed by the second active region 104. Hence, it is not necessary to accurately control the wavelength of the excitation light; thus, it is not necessary to tune the 5 wavelength of the excitation light or to control the temperature, and this makes the control easy.

Example 2

FIG. 2 is a schematic cross-sectional view 10 illustrating an example of a light emission device, which includes the vertical cavity surface emitting semiconductor laser as shown in FIG. 1.

In this example, the same reference numbers are used for the same elements as those in the previous 15 example, and overlapping descriptions being omitted.

As illustrated in FIG. 2, a VCSEL 202, as shown in FIG. 1, and an excitation semiconductor laser 203 are disposed on a silicon substrate 201. For example, the VCSEL 202 and the excitation semiconductor laser 203 20 are attached to the silicon substrate 201 by using a metal solder superior in thermal conductivity. For example, the excitation semiconductor laser 203 is a Fabry-Perot resonating semiconductor laser emitting a laser beam at a wavelength of  $0.85 \mu\text{m}$ .

25 A step is formed on the silicon substrate 201

so that active layers of the excitation semiconductor laser 203 and the multiple quantum well second active region 104 formed from GaAs/Al<sub>0.3</sub>Ga<sub>0.7</sub>As have nearly the same height.

5           The oscillation wavelength of the excitation semiconductor laser 203 is 0.85 μm, the same as the bandgap wavelength (0.85 μm) of the multiple quantum well second active region 104 formed from GaAs/Al<sub>0.3</sub>Ga<sub>0.7</sub>As of the VCSEL 202; hence, the second active region 104 of  
10          the VCSEL 202 can be optically excited to induce the VCSEL 202 to oscillate. Due to this, it is possible to increase the photon density in the VCSEL 202 while being in synchronization with the light in the VCSEL 202 generated by oscillation induced by current injection,  
15          and it is possible to increase the relaxation oscillation frequency fr of the VCSEL 202. As a result, by inputting a bias current and a modulation signal to the multiple quantum well active region 106 of the VCSEL 202, the light emission device of the present example is capable  
20          of large capacity optical transmission over 10 Gbps.

With the semiconductor laser 203, acting as the external excitation light source, being integrated on the silicon substrate 201, the light emission device of the present example can be made compact.

Example 3

FIG. 3 is a schematic cross-sectional view illustrating another example of the vertical cavity surface emitting semiconductor laser (VCSEL) according to 5 the present invention.

As illustrated in FIG. 3, an n-type distributed Bragg reflection mirror (DBR) 302 is disposed on an n-type GaAs substrate 301.

The n-type distributed Bragg reflection mirror 10 (DBR) 302 is formed by alternately stacking an n-type GaAs layer and an n-type Al<sub>0.9</sub>Ga<sub>0.1</sub>As layer, each of which has a thickness of 1/4 wavelength.

In addition, a first spacer layer 303 formed from GaAs, a multiple quantum well active region 304 15 formed from GaInNAs/GaAs, acting as the first active region, a second spacer layer 305 formed from GaAs, a p-type AlAs layer 108, a third spacer layer 306 formed from p-type GaAs, a multiple quantum well active region 307 formed from GaInNAs/GaAs, acting as the second active 20 region, a fourth spacer layer 308 formed from GaAs, a multiple quantum well active region 309 formed from GaInNAs/GaAs, acting as a third active region, and a non-doped DBR 310 are stacked sequentially on the n-type distributed Bragg reflection mirror (DBR) 302.

25 Here, the non-doped DBR 310 is formed by

alternately stacking a non-doped GaAs layer and a non-doped  $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$  layer, each of which has a thickness of  $1/4$  wavelength.

The stacked structure is etched from the top  
5 surface thereof up to the middle of the third spacer  
layer 306 to make the etched portion of the stacked  
structure a cylindrical shape, thereby forming a first  
mesa structure. In addition, the stacked structure is  
further etched up to the n-type distributed Bragg  
10 reflection mirror (DBR) 302 to make the etched portion of  
the stacked structure a rectangular shape, thereby  
forming a second mesa structure larger than the first  
mesa structure.

The p-type AlAs layer 108 is selectively  
15 oxidized from a side surface of the second mesa structure,  
thereby forming an  $\text{AlO}_x$  insulating region 110.

A p-side electrode 112 is formed on the bottom  
of the first mesa structure (the top of the second mesa  
structure), and an n-side electrode 113 is formed on the  
20 back surface of the n-type GaAs substrate 301.

In the VCSEL illustrated in FIG. 3, holes  
injected from the p-side electrode 112 and electrons  
injected from the n-side electrode 113 recombine and  
result in light emission in the multiple quantum well  
25 first active region 304 formed from  $\text{GaInNAs}/\text{GaAs}$ , hence

emitting light at a wavelength of 1.3  $\mu\text{m}$ . At this moment, since the current is blocked by the AlO<sub>x</sub> insulating region 110, the current is concentrated beneath the portion of the p-type AlAs layer 108 not being 5 selectively oxidized, hence the current distribution is narrowed.

The light emitted from the first active region 304 resonates in the resonator between the n-type distributed Bragg reflection mirror (DBR) 302 and the 10 non-doped DBR 310, and a laser beam is emitted upward perpendicular to the substrate.

According to the present embodiment, in addition to the multiple quantum well first active region 304 formed from GaInNAs/GaAs, which emits light due to 15 current injection, the VCSEL includes the multiple quantum well second active region 307 formed from GaInNAs/GaAs, and the multiple quantum well third active region 309 formed from GaInNAs/GaAs. The multiple quantum well second active region 307 and the multiple quantum well third active region 309 do not have electrodes for 20 injecting currents.

With the excitation light being continuously injected from the outside to the second active region 307 and the third active region 309 through an light outgoing 25 portion of the VCSEL, the VCSEL oscillates due to the

external excitation light and emits a laser beam at a wavelength of 1.3  $\mu\text{m}$ .

With the excitation light being continuously injected into the second active region 307 and the third 5 active region 309 to induce oscillation in the second active region 307 and the third active region 309, by modulating the injection current flowing in the first active region 304, the carrier density in the first active region 304 changes, and the intensity of output 10 laser is modulated. Thus, the photon density in the second active region 307 and the third active region 309 generated by the external excitation light are added at the same mode to the photon density generated in the first active region 304 by current injection. Hence, the 15 photon density in the VCSEL can be increased, and it is possible to increase the relaxation oscillation frequency fr of the VCSEL, and attain high speed modulation.

In this example, because there are two active layers, which are excited by light from the outside, the 20 density of carriers stored in each of the active layers can be lowered. Therefore, compared to the VCSEL in the first example, gain saturation can hardly occur even at a high photon density; hence, it is possible to further increase the relaxation oscillation frequency.

25 In addition, it is not necessary to form pn

junctions in the second active region 307 and the third active region 309, which are excited by external excitation light and emit light. Therefore, there are fewer limitations to the positions to form the active 5 layers.

In FIG. 3, it is illustrated that plural active regions are provided in the resonator, but the optically excited active regions may be provided in the DBR 302. Alternatively, plural resonators coupled with 10 each other may be constructed, and the optically excited active regions may be provided in each of the resonators. In this situation, in order to increase the coupling efficiency between light in the VCSEL and the active layers, it is preferable that the active regions be 15 provided at anti-node positions of the optical standing wave distribution in the VCSEL.

Although the number of the active regions is increased, because it is not necessary to provide electrode terminals for current injection, the 20 fabrication process does not become complicated.

In this example, the active regions are formed from GaInNAs, which is a mixed crystalline semiconductor of nitrogen and a group-V element (As). Hence, the active regions, which emit light at a band of  $1.3 \mu\text{m}$ , can be 25 epitaxially grown on the GaAs substrate 301. It is known

that dispersion in a silica optical fiber becomes zero at a wavelength of  $1.31 \mu\text{m}$ . Therefore, with the VCSEL of this example, it is possible to construct an optical transmission system involving less transmission  
5 limitations caused by the dispersion even at a transmission speed over 10 Gbps.

Example 4

FIG. 4 is a schematic cross-sectional view  
10 illustrating an example of a light emission device including the vertical cavity surface emitting semiconductor laser as shown in FIG. 3.

In this example, the same reference numbers are used for the same elements as those in the previous  
15 examples, and overlapping descriptions being omitted.

As illustrated in FIG. 4, a VCSEL 402 for use of excitation emits a continuous laser beam, and the output laser beam enters a polarized beam splitter 403. The polarization direction of the light from the VCSEL  
20 402 is set such that the light can be reflected on the polarized beam splitter 403, thereby, the light output from the VCSEL 402 is bent by 90 degrees, and is incident on an exit plane of a VCSEL 401, which is the same as that shown in FIG. 3. The oscillation wavelength of the  
25 VCSEL 402 is  $0.98 \mu\text{m}$ .

Because the oscillation wavelength of the VCSEL 402 for excitation is shorter than the oscillation wavelengths of  $1.31 \mu\text{m}$  of the multiple quantum well second active region 307 formed from GaInNAs/GaAs and the 5 multiple quantum well third active region 309 formed from GaInNAs/GaAs of the VCSEL 402, the second active region 307 and the third active region 309 can be optically excited to induce oscillation in the second active region 307 and the third active region 309. Due to this, it is 10 possible to increase the photon density in the VCSEL 401 while being in synchronization with the light in the VCSEL 401 generated by oscillation induced by current injection, and it is possible to increase the relaxation 15 oscillation frequency  $f_r$  of the VCSEL 401.

The polarization direction of the modulation optical signal output from the VCSEL 401 is set such that the light can pass through the polarized beam splitter 403; thus, the light output from the VCSEL 401 is emitted upward without being reflected.

According to the light emission device including the VCSEL having an increased relaxation oscillation frequency, it is possible to realize large capacity transmission over 10 Gbps.

In addition, because the external excitation 25 light source is a vertical cavity vertical cavity surface

emitting semiconductor laser, it is possible to reduce power consumption of the light emission device, and reduce cost of the light emission device.

5           Example 5

FIG. 5A is a schematic cross-sectional view illustrating another example of the vertical cavity surface emitting semiconductor laser (VCSEL) according to the present invention.

10           In this example, the same reference numbers are used for the same elements as those in the previous examples, and overlapping descriptions being omitted.

As illustrated in FIG. 5A, an n-type distributed Bragg reflection mirror (DBR) 302 is disposed 15. on an n-type GaAs substrate 301.

The n-type distributed Bragg reflection mirror (DBR) 302 is formed by alternately stacking an n-type GaAs layer and an n-type  $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$  layer, each of which has a thickness of 1/4 wavelength.

20           A first spacer layer 501 formed from GaAs, a multiple quantum well second active region 502 formed from GaInNAs/GaAs, a second spacer layer 503 formed from GaAs, a p-type AlAs layer 108, a third spacer layer 504 formed from p-type GaAs, a multiple quantum well first 25 active region 505 formed from GaInNAs/GaAs, a fourth

spacer layer 506 formed from GaAs, and a n-type DBR 507 are stacked sequentially on the n-type distributed Bragg reflection mirror (DBR) 302.

Here, the n-type DBR 507 is formed by  
5 alternately stacking a n-type GaAs layer and a n-type Al<sub>0.9</sub>Ga<sub>0.1</sub>As layer, each of which has a thickness of 1/4 wavelength.

In the example shown in FIG. 5A, a VCSEL 520 for generating modulation optical signals and a  
10 semiconductor laser 521 for excitation are integrated together on the n-type GaAs substrate 301.

In the VCSEL 520, the stacked structure is etched from the top surface thereof up to the middle of the third GaAs spacer layer 504 to make the etched  
15 portion of the stacked structure a cylindrical shape, thereby forming a first mesa structure. In addition, the stacked structure is further etched up to the n-type distributed Bragg reflection mirror (DBR) 302 to make the etched portion of the stacked structure a rectangular shape, thereby forming a second mesa structure larger  
20 than the first mesa structure.

The p-type AlAs layer 108 is selectively oxidized from a side surface of the second mesa structure, thereby forming an AlO<sub>x</sub> insulating region 110.

25 Protons are implanted in the area near the

first active layer 505 except for the center portion, and a high resistance region 508 is formed.

An n-side ring electrode 113 is formed on the top of the first mesa structure except for a light 5 outgoing portion. A p-side electrode 112 is formed on the bottom of the first mesa structure (the top of the second mesa structure).

A light-shielding layer 111 is arranged on the side surface of the first mesa structure

10 The semiconductor laser 521 for excitation is arranged to be close to and beside the VCSEL 520, forming a Fabry-Perot resonating semiconductor laser with an edge reflection mirror being formed by etching.

FIG. 5B is a schematic cross-sectional view  
15 illustrating the semiconductor laser 521 along the A-B line in FIG. 5A.

The stacked structure illustrated in FIG. 5B, is the same as the VCSEL 520 in FIG. 5A.

The stacked structure in FIG. 5B is etched  
20 from the top surface thereof up to the middle of the third GaAs spacer layer 504 to form a first ridge stripe structure. In addition, the stacked structure is further etched up to the n-type distributed Bragg reflection mirror (DBR) 302 to form a second ridge stripe structure  
25 having a width greater than the first ridge stripe

structure.

The p-type AlAs layer 108 is selectively oxidized from a side surface of the second ridge stripe structure, thereby forming an AlO<sub>x</sub> insulating region 110.

5           A p-side electrode 511 is formed on the bottom of the first ridge stripe structure (the top of the second ridge stripe structure), and an n-side electrode 510 is formed on the back surface of the n-type GaAs substrate 301.

10           In the semiconductor laser 521, which is used for excitation, a current injected from the p-side electrode 511 is concentrated to a center portion of the ridge stripe structure due to the AlO<sub>x</sub> insulating region 110, and is injected into the multiple quantum well 15 second active region 502 formed from GaInNAs/GaAs, and emits light at a wavelength of 1.3 μm.

The n-type distributed Bragg reflection mirror (DBR) 302 and the n-type DBR 507 function as clad layers, confining light in the perpendicular direction.

20           Because the AlO<sub>x</sub> insulating region 110 which is selectively oxidized has a lower refractive index than the portion of the p-type AlAs layer 108 which is not selectively oxidized, a difference of the refractive index in the horizontal direction results. Because of the 25 difference of the refractive index of the AlO<sub>x</sub> insulating

region 110 in the horizontal direction and the first ridge stripe structure, light is confined also in the horizontal direction.

Light resonates between a pair of edge  
5 reflection mirrors formed by dry etching, and the oscillating laser is extracted in the horizontal direction.

On the other hand, in the VCSEL 520, holes injected from the p-side electrode 112 and electrons  
10 injected from the n-side electrode 113 recombine and result in light emission in the multiple quantum well first active region 505 formed from GaInNAs/GaAs hence, emitting light at a wavelength of  $1.3 \mu\text{m}$ . At this moment, the current is concentrated in a mesa center by the high  
15 resistance region 508. Because of a difference of the refractive indexes of the  $\text{AlO}_x$  insulating region 110 and the p-type AlAs layer 108, light is confined in the horizontal direction, and this reduces refraction loss.

The light emitted from the first active region  
20 505 resonates in the resonator between the n-type distributed Bragg reflection mirror (DBR) 302 and the n-type DBR 507, and a laser beam is emitted upward perpendicular to the substrate.

As described above, in addition to the  
25 multiple quantum well first active region 505 formed from

GaInNAs/GaAs, which emits light due to current injection, the VCSEL 520 includes the multiple quantum well second active region 502 formed from GaInNAs/GaAs without a current injection mechanism. The second active region 502 of the VCSEL 520 has the same height as the active region 502 of the neighboring semiconductor laser 521; thus, the external excitation light can be injected from the side surface of the second mesa structure into the second active region 502.

With the excitation light generated by the semiconductor laser 521 being continuously injected to the second active region 502, a laser beam is emitted from the second active region 502 having a wavelength corresponding to a bandgap of the second active region 502 at  $1.3 \mu\text{m}$ . When the intensity of the excitation light is increased to be over a specified threshold value, optically-excited laser oscillation occurs in the VCSEL 520.

With the excitation light being continuously injected to the second active region 502 to induce oscillation in the second active region 502, by modulating the injection current flowing in the first active region 505, the carrier density in the first active region 505 changes, and the intensity of output laser is modulated. Thus, the photon density in the

second active region 502 generated by the external excitation light is added at the same mode to the photon density generated in the first active region 505 by current injection. Hence, the photon density in the VCSEL 520 can be increased, and it is possible to increase the relaxation oscillation frequency  $f_r$  of the VCSEL 520, and attain high speed modulation.

According to the light emission device of this example, because the VCSEL 520 for generating modulation optical signals and the semiconductor laser 521 for excitation are integrated together on the same n-type GaAs substrate 301, it is possible to make the light emission device more compact, reduce the number of parts in the light emission device, simplify the mounting and assembly process, and reduce cost of the light emission device.

#### Example 6

FIG. 6 is a schematic cross-sectional view illustrating another example of the vertical cavity surface emitting semiconductor laser (VCSEL) according to the present invention.

As illustrated in FIG. 6, an n-type distributed Bragg reflection mirror (DBR) 601 is disposed on an n-type GaAs substrate 301.

The n-type distributed Bragg reflection mirror (DBR) 601 is formed by alternately stacking an n-type GaAs layer and an n-type  $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$  layer, each of which has a thickness of 1/4 wavelength (wavelength:  $0.98\mu\text{m}$ ).

5 In addition, a first spacer layer 602 formed from  $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ , a multiple quantum well active region 603 formed from GaInAs/GaAs, a second spacer layer 604 formed from  $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ , and a p-type DBR 605 are stacked sequentially on the n-type distributed Bragg reflection  
10 mirror (DBR) 601.

Here, the p-type DBR 605 is formed by alternately stacking a p-type GaAs layer and a p-type  $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$  layer, each of which has a thickness of 1/4 wavelength (wavelength:  $0.98\mu\text{m}$ ).

15 In addition, a non-doped DBR 606 is deposited on the p-type DBR 605.

Here, the non-doped DBR 606 is formed by alternately stacking a none-doped GaAs layer and a none-doped  $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$  layer, each of which has a thickness of  
20 1/4 wavelength (wavelength:  $1.3\mu\text{m}$ ).

In addition, a multiple quantum well second active region 607 formed from GaInNAs/GaAs, a first spacer layer 608 formed from p-type GaAs, a p-type AlAs layer 108, a second spacer layer 609 formed from GaAs, a  
25 multiple quantum well first active region 610 formed from

GaInNAs/GaAs, a third spacer layer 611 formed from GaAs, and a n-type DBR 612 are stacked sequentially on the non-doped DBR 606.

Here, the n-type DBR 612 is formed by  
5 alternately stacking a n-type GaAs layer and a n-type Al<sub>0.9</sub>Ga<sub>0.1</sub>As layer, each of which has a thickness of 1/4 wavelength (wavelength: 1.3 μm).

The stacked structure is etched from the top surface thereof up to the middle of the first spacer  
10 layer 608 formed from p-type GaAs to make the etched portion of the stacked structure a cylindrical shape, thereby forming a first mesa structure. In addition, the stacked structure is further etched up to the p-type distributed Bragg reflection mirror (DBR) 605 to make the  
15 etched portion of the stacked structure a cylindrical shape, thereby forming a second mesa structure larger than the first mesa structure.

The p-type AlAs layer 108 is selectively oxidized from a side surface of the first mesa structure,  
20 thereby, forming an AlO<sub>x</sub> insulating region 110.

Protons are implanted in the area near the multiple quantum well active region 603 formed from GaInAs/GaAs, except for the portion below the second mesa structure, and a high resistance region 508 is formed.

25 An n-side ring electrode 113 is formed on the

top of the first mesa structure except for a light outgoing portion. A p-side electrode 112 is formed on the bottom of the first mesa structure (the top of the second mesa structure). A p-side electrode 511 is formed on the 5 bottom of the second mesa structure. An n-side electrode 510 is formed on the back surface of the n-type GaAs substrate 301.

In the light emission device shown in FIG. 6, a VCSEL 620 for generating modulation optical signals and 10 a VCSEL 621 for excitation are integrated together on the n-type GaAs substrate 301. Specifically, the n-type distributed Bragg reflection mirror (DBR) 601, the first spacer layer 602, the multiple quantum well active region 603 formed from GaInAs/GaAs, the second spacer layer 604 15 formed from Al<sub>0.2</sub>Ga<sub>0.8</sub>As, and the p-type DBR 605 constitute the VCSEL 621 for excitation, and

the non-doped DBR 606, the multiple quantum well second active region 607 formed from GaInNAs/GaAs, the first spacer layer 608 formed from p-type GaAs, the 20 p-type AlAs layer 108, the second spacer layer 609 formed from GaAs, the multiple quantum well first active region 610 formed from GaInNAs/GaAs, the third spacer layer 611 formed from GaAs, and the n-type DBR 612 constitute the VCSEL 620 for generating modulation optical signals.

25 In the VCSEL 621, which is used for excitation,

holes injected from the p-side ring electrode 511 and electrons injected from the n-side electrode 510 recombine in the multiple quantum well active region 603 formed from GaInAs/GaAs, resulting in emission of light 5 at a wavelength of  $0.98 \mu\text{m}$  in the active region 603. At this moment, the current is concentrated in the mesa center by the high resistance region 508. The light emitted from the multiple quantum well active region 603 formed from GaInAs/GaAs resonates in the resonator 10 between the n-type distributed Bragg reflection mirror (DBR) 601 and the p-type DBR 605, and a laser beam is emitted upward perpendicular to the substrate.

On the other hand, in the VCSEL 620 for generating modulation optical signals, holes injected 15 from the p-side electrode 112 and electrons injected from the n-side electrode 113 recombine, resulting in emission of light at a wavelength of  $1.3 \mu\text{m}$  in the multiple quantum well second active region 607 formed from GaInNAs/GaAs. At this moment, the multiple quantum well 20 second active region 607 is excited by the light beam at  $0.98 \mu\text{m}$  from the VCSEL 621 below the second active region 607, and light is emitted from the second active region 607 having a wavelength corresponding to a bandgap of the second active region 607 at  $1.3 \mu\text{m}$ . When the 25 intensity of the excitation light is increased to be over

a specified threshold value, laser oscillation occurs in the VCSEL 620 due to optical excitation.

With the excitation light generated by the excitation VCSEL 621 being continuously injected into the 5 second active region 607 to induce oscillation in the second active region 607, by modulating the current to be injected into the first active region 610, the carrier density in the first active region 610 changes, and the intensity of output laser is modulated. Thus, the photon 10 density in the second active region 607 generated by the external excitation light is added at the same mode to the photon density generated in the first active region 610 by current injection. Hence, the photon density in the VCSEL 620 can be increased, and it is possible to 15 increase the relaxation oscillation frequency  $f_r$  of the VCSEL 620, and attain high speed modulation.

In addition, the multiple quantum well first active region 610 formed from GaInNAs/GaAs is doped with p-type impurities, for example, C, at a concentration of 20  $8 \times 10^{18} \text{ cm}^{-3}$ .

Due to this, the density of electrons required to be injected for laser oscillation decreases, and a differential gain  $g$  increases. As a result, it is possible to further increase the relaxation oscillation 25 frequency of the VCSEL device by a factor of 1.5. Due to

this effect, it is possible for the VCSEL 620, which generates modulation optical signals, to generate optical signals at 40 Gbps by direct modulation.

Because the VCSEL 620 for generating  
5 modulation optical signals and the VCSEL 621 for excitation are integrated together on the same n-type GaAs substrate, it is possible to make the light emission device more compact, reduce the number of parts in the light emission device, and reduce cost of the light  
10 emission device.

Because there are no external modulators or optical image-forming elements, it is possible to reduce the number of parts in the light emission device, simplify the mounting and assembly process, and reduce  
15 cost of the light emission device.

Further, even when the environmental temperature changes, because in the VCSEL 620 the laser oscillation induced by optical excitation and the laser oscillation induced by current excitation are always in  
20 synchronization with each other, it is not necessary to perform accurate temperature control in order to improve the relaxation oscillation frequency. Due to this, it is possible to construct a light emission device at low cost without electron cooling devices.

Example 7

FIG. 7 is a schematic view illustrating an optical transmission system according to the present invention.

5 As illustrated in FIG. 7, the optical transmission system includes an optical transmitting section 701, an optical reception section 702, and optical fiber cable 704.

10 The optical transmitting section 701 converts electrical signals to optical signals, and transmits the optical signals to the optical fiber cable 704.

15 The optical fiber cable 704 guides the optical signals. The optical fiber cable 704 includes two transmission lines for transmission and reception, respectively, and is capable of bi-directional communication.

The optical reception section 702 converts the optical signals to electrical signals.

20 The optical transmitting section 701 and the optical reception section 702 are accommodated in one package, and this package is called optical transmission and reception module 703.

25 For example, the light emission device as described in FIG. 6 is used as the light source in the optical transmitting section 701 of the optical

transmission system in FIG. 7.

The light emission device in FIG. 6 is able to increase the relaxation oscillation frequency, and capable of signal transmission at 40 Gbps with external  
5 modulators.

Because it is not necessary to perform accurate temperature control with electron cooling devices, the light emission device can be constructed at low cost. Hence, it is possible to construct an optical  
10 transmission system capable of optical transmission at 40 Gbps at low cost.

Example 8

FIG. 8 is a schematic cross-sectional view  
15 illustrating an example of the vertical cavity surface emitting semiconductor laser (VCSEL) according to the present invention.

As illustrated in FIG. 8, a non-doped first distributed Bragg reflection mirror (DBR) 801 is disposed  
20 on a semi-insulating GaAs substrate 101.

The non-doped distributed Bragg reflection mirror (DBR) 801 is formed by alternately stacking a non-doped  $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$  layer and a non-doped  $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$  layer, each of which has a thickness of 1/4 wavelength.

25 In addition, a first spacer layer 802 formed

from  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ , a multiple quantum well active region  
104 formed from  $\text{GaAs}/\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ , acting as the second  
active region, a second spacer layer 803 formed from n-  
type  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ , and a non-doped second DBR 804 are  
5 stacked sequentially on the non-doped distributed Bragg  
reflection mirror (DBR) 801.

Here, the non-doped second DBR 804 is formed  
by alternately stacking a non-doped  $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$  layer and  
a non-doped  $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$  layer, each of which has a  
10 thickness of  $1/4$  wavelength. The period of the stacked  
structure is less than the non-doped first DBR 801.

In addition, a third spacer layer 805 formed  
from n-type  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ , a multiple quantum well active  
region 106 formed from  $\text{GaAs}/\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ , acting as the  
15 first active region, a fourth spacer layer 806 formed  
from  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ , a p-type AlAs layer 108, and a p-type  
DBR 807 are stacked sequentially on the non-doped second  
DBR 804.

Here, the p-type DBR 807 is formed by  
20 alternately stacking a p-type  $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$  layer and a p-  
type  $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$  layer, each of which has a thickness of  
 $1/4$  wavelength.

The stacked structure is etched from the top  
surface thereof up to the middle of the third spacer  
25 layer 805 to make the etched portion of the stacked

structure a cylindrical shape, thereby forming a first mesa structure. In addition, the stacked structure is further etched up to the non-doped distributed Bragg reflection mirror (DBR) 801 to make the etched portion of 5 the stacked structure a cylindrical shape, thereby forming a second mesa structure larger than the first mesa structure.

The p-type AlAs layer 108 is selectively oxidized from a side surface of the first mesa structure, 10 thereby, forming an  $\text{AlO}_x$  insulating region 110.

A p-side ring electrode 112 is formed on the p-type DBR 807 except a light outgoing portion, and an n-side electrode 113 is formed on the bottom of the first mesa structure (the top of the second mesa structure).

15 A 45° reflection mirror 809 is arranged adjacent to one side of the second mesa structure, and a high reflectivity film 808 is disposed on the surface of the reflection mirror 809. The high reflectivity film 808 may be a metal film with an insulating film, or a 20 dielectric multilayer film.

In the VCSEL in FIG. 8, there are a first resonator sandwiched by the non-doped first DBR 801 and the non-doped second DBR 804, a second resonator sandwiched by the non-doped second DBR 804 and the p-type 25 DBR 807. The Bragg reflection wavelengths of the non-

doped first DBR 801, the non-doped second DBR 804, and the non-doped second DBR 804 and the p-type DBR 807 are all 0.85  $\mu\text{m}$ . In addition, it is designed that the length of each of the resonators equals an integral multiple of 5 an optical distance equivalent to 0.85  $\mu\text{m}$ . The stacking period of the non-doped second DBR 804 is 10, which is less than the stacking period of the non-doped second DBR 801; thereby, the two resonators optically couple with each other and form a resonance mode.

10           In the VCSEL illustrated in FIG. 8, holes injected from the p-side ring electrode 112 and electrons injected from the n-side electrode 113 recombine and result in light emission in the multiple quantum well first active region 106 formed from GaAs/Al<sub>0.3</sub>Ga<sub>0.7</sub>As in 15 the first resonator, hence, emitting light at a wavelength of 0.85  $\mu\text{m}$ . At this moment, since the current is blocked by the AlO<sub>x</sub> insulating region 110, the current is concentrated beneath the portion of the p-type AlAs layer 108 not being selectively oxidized, hence the 20 current distribution is narrowed.

         The light emitted from the first active region 106 resonates in the compound resonator obtained by coupling the non-doped first DBR 801, the non-doped second DBR 804, and the p-type DBR 807, and a laser beam 25 is emitted upward perpendicular to the substrate.

The external excitation light is reflected on the 45° reflection mirror 809, and is incident on the second active region 104 provided in the first resonator from a side surface of the second mesa structure. With 5 the excitation light being continuously injected into the second active region 104, light is emitted from the second active region 104 having a wavelength corresponding to a bandgap of the second active region 104 at 0.85 μm. When the intensity of the excitation 10 light is increased to be over a specified threshold value, optically-excited laser oscillation occurs in the VCSEL.

Because the first active region 106 has the same bandgap as the second active region 104, and the first active region 106 and the second active region 104 15 couple with each other to form the same resonance mode, the light generated by oscillation induced by current injection into the first active region 106 and the light generated by oscillation induced by optically exciting the second active region 104 have the same wavelength.

With the excitation light being continuously injected into the second active region 104 to induce 20 oscillation in the second active region 104, by modulating the injection current to the first active region 106, the carrier density in the first active region 106 changes, and the intensity of output laser is

modulated. Therefore, the photon density in the second active region 104 generated by the external excitation light is added at the same mode to the photon density generated in the first active region 106 by current injection. Hence, the photon density in the VCSEL can be increased, and it is possible to increase the relaxation oscillation frequency  $f_r$  of the VCSEL, and attain high speed modulation.

Because the first active region 106 and the second active region 104 are arranged to sandwich the non-doped second DBR 804 and are in different resonators, the external excitation light reflected from the 45° reflection mirror 809 selectively excites the second active region 104, but does not leak off to the first active region 106, to generate a coupling with the first active region 106. As a result, with the external excitation light, it is possible to increase the limit value of the current causing gain saturation in the first active region 106 without increasing the carrier density in the first active region 106. Therefore, it is possible to increase a signal-to-noise (S/N) ratio of modulation optical signals generated by modulation electrical signals applied on the first active region 106.

While the present invention is above described with reference to specific embodiments chosen for purpose

of illustration, it should be apparent that the invention  
is not limited to these embodiments, but numerous  
modifications could be made thereto by those skilled in  
the art without departing from the basic concept and  
5 scope of the invention.

This patent application is based on Japanese  
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